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Docket No.: 300111171-2 (1509-467)

PATENT

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of

David SIKHARULIDZE

U.S. Patent Application No. 10/698,028

Filed: October 31, 2003

For: BISTABLE NEMATIC LIQUID CRYSTAL DISPLAY DEVICE

Confirmation No. 7131

Group Art Unit: 1772

Examiner: Sow Fun Hon

SUBMISSION OF DECLARATION UNDER § 1.132

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450CERTIFICATION OF FACSIMILE TRANSMISSION
I HEREBY CERTIFY THAT THIS PAPER IS BEING FACSIMI-
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ON THE DATE SHOWN BELOWDonna L. Lizama
TYPE OR PRINT NAME OF PERSON SIGNING CERTIFICATIONDonna L. Lizama 6/2/06
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571-273-8300

FACSIMILE NUMBER

Sir:

Applicant forwards herewith a Declaration signed by the inventor, David Sikharulidze, Ph.D., who is an expert in the fields of liquid crystals and liquid crystal displays. Dr. Sikharulidze has testified as to why one of ordinary skill in the art would not have obviously combined the references relied on by the Examiner in the Final Rejection. In addition, Dr. Sikharulidze has testified that he has read the responses submitted by his undersigned attorneys on April 5, 2006, and agrees with the statements therein. The technical rationale set forth in Dr. Sikharulidze's Declaration, and the statements set forth in the April 5, 2006 Response, provide ample technical rationale as to why the Examiner's position is the result of hindsight. The Examiner has cast around to find references that disclose individual aspects of Applicant's invention. However, one of ordinary skill in the art would not have combined the references because they are, in actuality, directed to different types of liquid crystal technology, as set forth in Dr. Sikharulidze's Declaration and the arguments submitted in the May 8, 2006 response.

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Application No.: 10/698,028**Docket No.: 300111171-2 (1509-467)**

the May 8, 2006 response.

Based on the foregoing, and the Declaration, allowance is in order.

To the extent necessary, a petition for an extension of time under 37 C.F.R. 1.136 is hereby made. Please charge any shortage in fees due in connection with the filing of this paper, including extension of time fees, to Deposit Account 08-2025, and credit any excess fees to such deposit account.

Respectfully submitted,

David SIKHARULIDZE



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PATENT APPLICATION

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re the Application of

David SIKHARULIDZE

Group Art Unit: 1772

Application No.: 10/698,028

Examiner: SOW FUN HON

Filed: October 31, 2003

Docket No.: 1509-467

For: BISTABLE NEMATIC LIQUID CRYSTAL DISPLAY DEVICE

DECLARATION UNDER 37 C.F.R. §1.132

I, David Sikharulidze, hereby declare and state:

1. I am the inventor of the referenced application.
2. My Curriculum Vitae is attached as Exhibit 1. The Curriculum Vitae is accurate in all respects, except that U.S. equivalents for the degrees that were awarded are set forth.
3. The vast majority of publications listed in my Curriculum Vitae are in refereed journals, and therefore were subjected to peer review prior to publication.
4. As a result of my work experience and education, I am considered an expert by my peers in the fields of liquid crystals and liquid crystal displays.
5. I have carefully reviewed the Remarks portion of the April 5, 2006 response to the January 6, 2006 Office Action, as submitted by my attorneys, and agree with the statements set forth therein.
6. I have also carefully reviewed the April 17, 2006 Advisory Action issued by the Examiner of the U.S. Patent and Trademark Office, and do not agree with many of the allegations stated therein for the reasons set forth in the subsequent portions of this Declaration.

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7. Concerning the allegations in paragraph 3 of the Advisory Action, U.S. Patents 5,457,235 and 5,626,791 do not describe nematic liquid crystals (LCs) that exhibit ferroelectric features. On the contrary, the ferroelectric LCs of these two patents differ considerably from the nematic liquid crystals of claim 1. These patents only describe some materials and components, which might be useful to improve some parameters of liquid crystals, including ferroelectric liquid crystals. In contrast to ferroelectric liquid crystals, nematic liquid crystal materials do not exhibit intrinsic bistability. This property of liquid crystals is described in many liquid crystal handbooks (see for instance: Iam-Choon Khoo, Shin-Tson Wu, Optics and Nonlinear Optics of Liquid Crystals, World Scientific, 1993 (Exhibit 2); L.M. Blinov, V.G. Chigrinov. Electrooptic Effects in Liquid Crystal Materials, Springer, 1996 (Exhibit 3); P.G de Gennes and J.Prost. The Physics of Liquid crystals, second edition, Clarendon Press, Oxford, 1993 (Exhibit 4)).

8. In response to the allegation in paragraph 4, the Takano device is different from the Eguchi device because of the construction, LC materials and electro-optical effects thereof. Consequently, one of ordinary skill in the liquid crystal art would not have modified the Eguchi et al. device as a result of the disclosure in the Takano patent to form a bistable device with an orientation that enables modulation of polarized light due to reorientation of the LC molecules. While the Takano patent mentions improving contrast and response speed, there is no connection between these factors and obtaining first and second stable states in nematic LCDs.

Concerning paragraph 5, it is a scientific fact that a planar cell nematic liquid crystal, when switched between two equal zenithally reverted homeoplanar states, will produce results that are not optically distinguishable. The ferroelectric liquid crystal in the Eguchi cell (not ferroelectric nematic liquid crystal, as erroneously mentioned by the Examiner on page

4, line 1 of the Advisory Action), switches between two azimuthally different states. In this case, the molecules of the ferroelectric liquid crystal move in conical paths between two azimuthally distinguished planar states in response to applied unipolar pulses. U.S. patents 6,867,836 and 7,006,165, mentioned by the Examiner, are irrelevant because they describe devices that have very different constructions, alignment layers and driving methods from those of the Eguchi cell. Consequently, one of ordinary skill in the art would not have been motivated to consider the '836 or '165 patents in connection with the Eguchi cell.

U.S. Patent 7,006,165 describes a device which is driven by a combination of optical and electrical signals. One of the surfaces of this device has a specially designed alignment layer, providing two azimuthally different alignment profiles. The alignment of the LC changes depending on the polarization of light incident on the LC. Consequently, the nematic liquid crystal adopts two different azimuthal states. Also, this process can be controlled by heating, produced by incident light.

In U.S. Patent 6,867,836, the alignment layer is made by using a linear photopolymerization (LPP) technique, by patterning an alignment layer with small areas; the alignment layer contains profiles having different azimuth orientations. The device employs a chiral nematic LC. In response to the application of electric pulses, the molecules in the alignment layer adopt one of these orientations on the patterned surface.

From the above, the devices of the '836 and '165 patents are very different and use different techniques for alignment and switching of the nematic liquid crystal from the standard alignment of the Eguchi cell. Consequently, one of ordinary skill in the art who was interested in the Eguchi cell would not have paid any attention to the disclosures of the '836 and '165 patents.

9. In connection with paragraph 6, as mentioned previously, the Eguchi and Takano devices are very different and one of ordinary skill would not have been led by them to the combinations of independent claims 1 and 16 that require the LC material to have first and second stable states or first and second different orientations. A simple combination of Eguchi and Takano would not lead to the bistable nematic device of claims 1 and 16 because of the different constructions and electro-optical effects of these devices.

10. In response to paragraph 7, Applicant previously mentioned that the Eguchi device uses a pair of 90° cross Nicol polarisers. This statement was an answer to a previous incorrect remark of the Examiner that the Eguchi device uses one polarizer to distinguish between different optical states of the liquid crystal. One polarizer cannot distinguish between different optical states of the liquid crystal; two are needed.

11. Concerning paragraph 8, Figures 2, 3 and 5 of Eguchi and description thereof at column 7, line 56 through column 8, line 67 indicate the molecules (1) switch from one state to another due to electrical dipole moment, and (2) move in a conical path to switch between azimuthally distinguished planar stable states in response to opposite polarity pulses. As paragraph 8 states, the Eguchi device does not provide zenithal switching of the molecules. However, that is not what Applicant argued in the first full paragraph on page 5 of the April 5, 2006 response.

The point Applicant made in the April 5, 2006 response was in response to the Examiner's position about combining the Eguchi and Takano devices. Combining the Eguchi and Takano devices does not lead to a nematic bistable device, similar to the claimed device, because, in the Eguchi planar cell, a nematic liquid crystal mixture could be switched between two equal zenithally reverted molecular orientations, which can not be optically distinguished from each other. In this case, in response to pulses of a first polarity, the

molecules would have a vertical alignment close to a first of the cell surfaces and a horizontal alignment close to an opposite second cell surface at zero field. In response to pulses of a second polarity, the molecules would have a second orientation with a zenithally reverted orientation. Therefore, both states exhibit equal birefringent effects at zero field and optical responses can not be distinguished from each other.

12. In response to paragraph 9, Applicant notes that unlike the Crawford and Tanako devices, Applicant's claimed devices of claims 1 and 16, and the claims dependent on them, are based on an electro-optical orientational effect in nematic LCs that modulates polarized light. Therefore, as usual for an orientational effect, the molecules must be well aligned (for example as achieved by a rubbed polyimide layer) for best optical performance. The optical effect is achieved by locating the cell between two crossed polarizers. As known, in this case the intensity of transmitted light is defined as:

$$I = I_0 \sin^2 \alpha \sin^2 (\pi d \Delta n / \lambda),$$

where α = angle between a polarizer and director (alignment direction of nematic LC molecules), I_0 = intensity of polarized light, incident on the cell, d = thickness of the cell, Δn = optical anisotropy of the LC, λ = light wavelength. For maximum optical effect, the cell is located between polarizers so the angle between the director and polarizer is $\alpha = 45^\circ$. In this case $\sin^2 2\alpha = \sin^2 90^\circ = 1$ and the optical effect is maximized by: $I = I_0 \sin^2 (\pi d \Delta n / \lambda)$. The scattering effect in such a cell means that the LC molecules are randomly distributed in the cell. To estimate how the scattering effect influences the optical effect, it can be validly assumed that a first half of the molecules are oriented 45° with respect polarizers, to thereby provide maximum transmittance and the second half of the molecules are oriented parallel (or

orthogonal) to the polarizers, to thereby provide zero transmittance. In this case, the cell between the crossed polarizers transmits light in the same manner as the cell which has an angle between the director and polarizer of $\alpha = (45^\circ + 0^\circ) / 2 = 22.5^\circ$. Consequently, transmittance of the cell with a scattering effect is: $I_{\text{scatt}} = I_0 \sin^2(2 \times 22.5^\circ) \sin^2(\pi d \Delta n / \lambda) = I_0 \sin^2 45^\circ \sin^2(\pi d \Delta n / \lambda) = (I_0 / 2) \sin^2(\pi d \Delta n / \lambda)$, because $\sin^2 45^\circ = 1/2$. From this simple example it follows that in case of scattering effect, the optical effect is reduced at least by a factor of two compared to the optical effect provided only by the orientational effect of the cells of claims 1 and 16. This also confirms that the operational modes of the Eguchi and Tanako devices differ, and one of ordinary skill would not have combined these references to provide the device of claim 1 or 16.

13. In response to paragraph 10, the Bryan Brown device is not bistable, and uses a LC with negative dielectric anisotropy and specific alignment arrangements of the substrates to get good contrast and response time. Because the Bryan Brown device works in different ways and has a different construction from Applicant's claimed device, one of ordinary skill would not have modified the Eguchi cell to include any features of the Bryan Brown device.

14. In reply to paragraph 11, Thurston discloses that dissolving (mixing) a pleochroic dye into a liquid crystal provides optical contrast between the vertical and horizontal states. The Thurston liquid crystal is thus used with at least one polarizer (column 2073a, first paragraph below Fig.6), to distinguish between the different optical states of the liquid crystal. On the other hand, as has been mentioned, the examiner's proposed combination of the Eguchi and Takano devices leads to devices with light scattering effects, which is a different optical mode from the Thurston optical mode. There are not any

indications of switching between vertical and horizontal states in this device, which, by Thurston, can allow using a pleochroic dye with one polarizer.

In the claimed device the nanoparticles that are suspended in a pure nematic LC exhibit an electrical charge. It is not obvious that the mixture proposed by the Examiner, that includes dyes, will cause the same effect. In the claimed device, which employs an electrooptical composition that includes dyes, an optical effect can be achieved with one polarizer or without the polarizers, due to stabilization of vertical and horizontal orientations of molecules during switching.

15. In response to paragraph 12, claim 3 indicates the nanoparticles acquire an electrical charge to assist in providing bistable switching in our device.

16. Based on the foregoing, the Examiner's position and arguments are incorrect.

I hereby declare that all statements made herein of my own knowledge are true, and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine and/or imprisonment under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application or any patent issuing therefrom.

Date: 02/06/2006

p. Sikharulidze
David SIKHARULIDZE

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CURRICULAM VITAE**SIKHARULIDZE DAVID**

1970 – Masters of Science in Physics, Tbilisi State University;

1980 – PhD in Physics and Mathematics from Tbilisi State University;

1995 - Doctor of Science in Physics and Mathematics from Georgian Technical University

1986-2000 - Head of Optical Image Solid State Converters Laboratory (Institute of Cybernetics of Georgian Academy of Sciences)

1997-2000 - Senior researcher of National Institute of Matter Physics and Calabria Scientific Park, c/o Physics Department, University of Calabria

Since September 2000 at present – Research Scientist of Hewlett-Packard Laboratories Bristol

Awards:

1987 – Silver Medal from Exhibition of National Achievements of USSR
(for developing : Fast liquid crystal image converter).

1989 - Winner of State Prize of Georgian Republic in Science
(for developing : Liquid crystals with induced spiral structure and their application in display systems)

Visits:

Priv.-Doz. Technical University Berlin, Laboratory of Liquid crystals (Nov.-Dec.1994, Oct.-Dec.1995, Feb.- Apr.1997);

Expertise:

electrooptics of nematic, cholesteric, ferroelectric, nematic discotic liquid crystals;
polymer/ liquid crystal systems(PDLC,gels,anisotropic network);
bistable effects in nematic and cholesteric liquid crystals;
controlled diffractive effects(grating) in cholesteric liquid crystal;
thermo and photooptics of cholesteric liquid crystals;
optical addressing of liquid crystals and electroluminescent systems;
optically addressed spatial light modulators and optical image transducers;
solid state night vision systems, optical limiting;
optical liquid crystalline memory(optical RAM) for optical computing systems.
electrophoretic effects in liquid crystals,
electrooptics of nematic liquid crystals colloids,
bistable effects and devices.

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Exhibit 1

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LIST OF PUBLICATIONS OF D.SIKHARULIDZE

Books

- D.G.Sikharulidze, G.S.Chilaya.** *Image Transducers Based on MIS-Electrooptical material structure*, Moscow, Radio I Swiaz, 1986, (in Russian).
K.D.Vinokur, D.G.Sikharulidze, G.S.Chilaya, Z.M.Elashvili. *Liquid Crystals with Helical Structure and Their Applications in Displays*. Tbilisi, Metzniereba, 1988, (in Russian).

Selected publications

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2. **G.Chilaya, D.Sikharulidze.** Induced ferroelectric salicylidenaniline liquid crystals: electrooptical properties and applications. *Ferroelectrics*, 1991, V.114, p.329-343.
3. **A.Chanishvili, G.Chilaya, D.Sikharulidze.** Light modulator based on optically active nematic-chiral liquid crystal structure. *Mol.Cryst.Liq.Cryst.*, V.207, 1991, p.53-57.
4. **D.Sikharulidze, G.Chilaya.** New protective light valve with local modulation - low-ohmic semiconductor-liquid crystal. Abstracts 14-th Intern. liquid crystal conf., Pisa(Italy), 1992, Vol.II, J-P47, p.815
5. **A.Chanishvili, G.Chilaya, D.Sikharulidze.** Electrooptic effect in optically active nematic-chiral liquid crystal structure. *Applied Optics*, 1994, v.33, No.16, pp 3482-3485
6. **D.Sikharulidze G.Chilaya.** The effect of optically addressed spatial modulation of light in the structure of low ohmic semiconductor-liquid crystal without applied voltage. Abstr. 15 th Intern.LC conference, July, 3-8, 1994, Budapest (Hungary), K-P39, p.933
7. **G.Chilaya, A.Chanishvili, G.Petriashvili and D.Sikharulidze.** Anomalous reflection at selective cholesteric-to-smectic phase transition. *Mol.Cryst.Liq.Cryst.*, 1995, v.261, pp 233-239
8. **G.Chilaya, A.Chanishvili, D.Sikharulidze.** Optically active(cholesteric with intermediate chirality) LC structure for light modulation. *Proc.SPIE*, 1995, v.2372, pp 96-100
9. **G.Chilaya, G.Hauck, H.-D.Koswig and D.Sikharulidze.** Electric field controlled colour effect in cholesteric LCs and polymer-dispersed cholesteric LCs. *J.of Appl.Phys.* 80(3), August 1996 ; pp 1907-1909
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11. **G.Chilaya, A.Chanishvili, G.Petriashvili and D.Sikharulidze.** New pretransitional liquid crystal phase with anomalous selective reflection. *Mol.Materials.*, v.8, 1997, pp. 245-255
12. **A.Chanishvili, D.Sikharulidze, G.Chilaya, G.Petriashvili.** Electrooptics of " amorphous" cholesteric structures with intermediate chirality. *Mol.Materials.*, v.8, 1997, 295-299
13. **D.Sikharulidze, G.Chilaya, K.Praefcke, D.Blunk.** First observation of an optically controlled electro-optic effect in nematic-discotic liquid crystals. *Liquid Crystals*, v.23, N 3, 1997, pp 439- 442
14. **R.Macdonald, P.Meindl, G.Chilaya, D.Sikharulidze.** Photoexcitation of space charge fields and reorientation of a nematic liquid crystals of discotic molecules. *Optics Commun.* 150, 1998, pp 195-200.
15. **L.M.Blinov, S.P.Palto, S., D.G. Sikharulidze, V.Yakovlev.** Assymetric electrooptical switching of a nematic cell controlled by a corona poled ferroelectric polymer layer. *Appl. Phys. Lett.* v.72, N 25, 1998, pp 3377- 3379.
16. **A.Chanishvili, G.Chilaya, G.Petriashvili, D.Sikharulidze.** Optics and electrooptics of blue phases. Abstracts 17-th Intern. liquid crystal conf., Strasbourg(France), 1998, P2-200. p.P-137

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17. R. Macdonald, P. Meindl, G. Chilaya, D. Sikharulidze. Reorientation of a Nematic Liquid Crystal of Discotic Molecules by Photoinduced Space Charge Fields. *Mol.Cryst.Liq.Cryst.* vol.320, , 1998, p.115
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19. D.Sikharulidze, A.Tchanishvili, G.Petriashvili, N.Scaramuzza, R.Barberi, R.Bartolino. Polarity sensitive bistable color effect in cholesteric liquid crystals with an asymmetric polymer network. *Appl. Phys. Lett.* V.75, N 7, 1999.p.1013
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21. D.Sikharulidze, Nanoparticles: a approach to controlling an electrooptical behaviour of nematic liquid crystals, *Appl. Phys. Lett*, 86, 0333507 (2005)
22. D.Sikharulidze, Electrophoretically controlled nematic: A novel approach for LCD technology, *Proc. EuroDisplay 2005*, 546 (2005)

Patents:

6 USSR Patents , N 506243, N 580778, N 528824, N 680462, N 807833, N 812030,
1 Republic of Georgia patent, U475

US Patents:

US6970211, US20040144953, US20050094087, US20050206831, US20050243264
Patents GB, GB2394781A, GB2404260A, GB2407646A, GB2407645A, GB2412180A,
GB2413646A
Patent Japan, JP 2004163867A

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SERIES IN NONLINEAR OPTICS

OPTICS AND NONLINEAR OPTICS OF LIQUID CRYSTALS

Iam-Choon Khoo
Pennsylvania State Univ.

Shin-Tson Wu
Hughes Research Lab.

World Scientific
Singapore • New Jersey • London • Hong Kong

This book is dedicated to:

Richard, Paul and C. S. Khoo

Janet, Benjamin and Cho-Yan Wu

Exhibit 2

takes place. The liquid crystal directors respond to the square amplitude of the external field. Thus, electric field-induced molecular reorientation of a nematic LC does not depend on the polarity of the field. Because the final states of the nematic director axis can be controlled continuously by the applied field, a normal nematic device tends to have large gray scales. Gray level is an important requirement for high density information displays.

Once the external field is completely removed, the liquid crystal directors relax back to their initial states through elastic restoring forces. The magnitude of this elastic force depends on the curvatures of the directors. The larger the director deformation, the larger the restoring force. Therefore, the decay time of a nematic liquid crystal device depends on the detailed operation conditions and the material employed. The typical response time of a nematic liquid crystal device is in the range of 10–100 ms.

(ii) Ferroelectrics

For ferroelectric liquid crystals (FLCs), two operation modes have been frequently employed for modulating light: (a) surface-stabilized FLC (SSFLC) in the smectic-C* phase,¹⁸ and (b) soft-mode FLC (SMFLC) in the smectic-A* phase.²⁰ The SSFLC molecules possess an intrinsic spontaneous polarization (P_s). When an external field is applied normal to P_s , the ferroelectric torque ($P_s \times E$) drives the LC directors around the tilt cone (the tilt angle θ remains constant and azimuthal angle ϕ varies) to another stable state and stays there unless a second field with an opposite sign is applied. The response time of an FLC device is inversely proportional to $P_s \cdot E$. The value of P_s ranges from 1 to 10^3 nC, depending on the LC materials. The applied electric field is about 10 V/ μ m. Thus, the response time of an FLC device is generally in the range of 1–100 μ s.

In the soft-mode effect (or electroclinic effect), the field-induced director tilt angle θ is linearly proportional to E at low field, whereas the azimuthal angle ϕ remains constant. Thus, gray scale is available in the SMFLC devices. However, the field-induced tilt angle is rather small. This leads to a smaller optical effect than the SSFLC. In order to achieve a uniform molecular rotation in an SSFLC cell, the layer thickness is usually limited to about 2 μ m. A large area, uniform alignment of SSFLC cell is not easy to obtain. On the other hand, SMFLC does not have such a stringent LC layer thickness limitation as SSFLC. Also, the surface alignment of SMFLC is a relatively easy task.

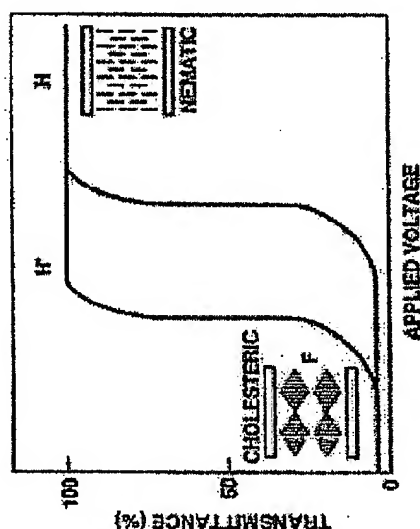


Fig. 2.2. Electric field-induced cholesteric-nematic phase change. At low voltages, the cell is in the cholesteric phase F . As the voltage increases, the cell is driven to homotropic nematic phase H . When the voltage is reduced, an intermediate metastable state (nematic phase H') exists. (Refract after Ref. 8.)

Once the voltage is removed completely, the liquid crystal directors return to their initial scattering states within a few milliseconds.

2.1.4. Field-induced director-axis reorientation

Field-induced director-axis reorientation on aligned nematic and ferroelectric liquid crystals is one of the most common electro-optic effects employed for modulating light. Many alignment methods have been developed for various applications employing nematic liquid crystals. For examples, 90° twist,¹⁰ homotropic (also called perpendicular) alignment,¹¹ 45° twist,¹² π -cell,¹³ and a variety of supertwist cells.^{14–18} Each alignment exhibits its own unique features and also drawbacks. For ferroelectric liquid crystals, the surface-stabilization alignment method for smectic-C phase,¹⁹ and the electroclinic effect for smectic-A phase²⁰ are both fundamentally interesting and practically important.

(i) Nematics

In nematics, the electric field-induced polarization of a LC molecule follows the field up to a few MHz of frequency before the dielectric relaxation

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Electrooptic Effects in Liquid Crystal Materials

With 221 Illustrations



Exhibit 3

a variety of azo- and anthraquinone dyes of T- and L-T-types, having certain advantages in practical applications. The commercial dyes developed by NIOPIK (Russia) and BDH (UK) are characterized by the following set of parameters (Table 2.2).

2.4 Viscoelastic Properties

The viscoelastic properties of liquid crystals are very important, and mainly determine the behavior of liquid crystals in external electric fields, defining such characteristics as controlling voltages, steepness of the transmission-voltage curve, response times, etc. Now only the phenomenological theory of the viscoelastic properties of nematic liquid crystals is essentially complete [18, 26].

In this section we will:

- (i) briefly outline the main conclusions of these theories;
- (ii) show the dependence of the viscoelastic constants of nematic liquid crystals on the structure and temperature; and
- (iii) discuss certain ideas as to how to develop new liquid crystal mixtures with given viscoelastic parameters.

We will also describe the main methods for the measurement of these parameters.

2.4.1 Elasticity

The basic difference between deformations in a liquid crystal and in a solid is that in liquid crystals there is no translational displacement of the molecules on distortion of a sample. This is due to "slippage" between liquid layers. A purely shear deformation of a liquid crystal conserves elastic energy. The elasticity of an isotropic liquid is related to changes in density. In liquid crystals, variations in density can also be characterized by a suitable modulus, but the elasticity which is related to the local variation in the orientation of the director is their principal characteristic.

In the theories of the elasticity of nematic liquid crystals the following assumptions are made:

1. Director $L(r)$ reorients smoothly as compared with the molecular dimension of a liquid crystal. Thus, we may conclude that the order parameter S remains constant throughout the whole volume of a liquid crystal at a fixed temperature T , while only the director field $L(r)$ varies in accordance with external electric (or some other) fields.

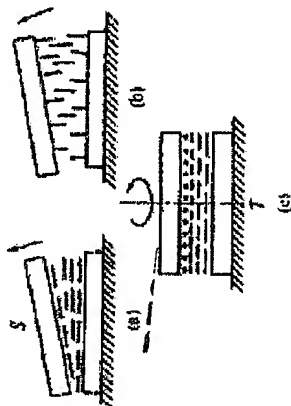


FIGURE 2.17. (a) S deformation (splay), (b) B deformation (bend), and (c) T deformation (twist) in an oriented layer of a nematic liquid crystal.

2. The only curvature strains of the director field which must be considered correspond to the splay, bend, and twist distortions (Fig. 2.17). Other types of deformation either do not change the elastic energy (e.g., the above mentioned pure shears) or are forbidden due to the symmetry. In nematic liquid crystals the cylindrical symmetry of the structure, as well as the absence of polarity (head to tail symmetry) must be taken into account.

3. Following Hooke's law, only squares of the director deformations $(\partial L_i / \partial x_j)^2$, where $i, j = x, y, z$, are included in the expression for the free energy. At the same time attention is paid only to the "pure volume" elastic terms: $\{L(r), r \in V\}$. All the terms which could be expressed via the surface director field: $\{L(r), r \in S\}$ are omitted.

In view of these suggestions the density of the free volume elastic energy (Frank's energy) of a nematic liquid crystal could be written as

$$g = \frac{1}{2} [K_{11}(\text{div } L)^2 + K_{22}(L \cdot \text{curl } L)^2 + K_{33}(L \times \text{curl } L)^2]. \quad (2.24)$$

Equation (2.24) forms the basis for examining almost all electrooptical and magnetooptical phenomena in nematic liquid crystals. The first term in (2.24) describes the S deformation (splay), the second term describes the T deformation (twist), and the third term describes the B deformation (bend). These three types of deformation are illustrated in Fig. 2.17.

In cholesteric (or chiral nematic) liquid crystals the situation is very close to usual nematics. However, due to the chirality of the molecules, the lowest state of elastic energy in cholesterics does no longer correspond to the uniform director orientation, but to the twisted one with a pitch $P_0 = 2\pi/q_0$, where q_0 is the wave vector of cholesteric. Thus for cholesterics the second term in expression (2.24) must be rewritten as

$$K_{22}(L \cdot \text{curl } L)^2 \rightarrow K_{22}(L \cdot \text{curl } L + q_0)^2, \quad (2.25)$$

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where positive and negative q values correspond to the left- and right-hand helix, respectively.

The theory of the elasticity of smectic liquid crystals has its own features. Deformations related to a change in the spacing between the layers are common to all smectic phases. The deformations is, in general, not related to a change in director orientation, and have an additional modulus of elasticity B occurs.

In smectic A liquid crystals the only allowed deformation is specific undulation of the smectic layers, such that interlayer distance is kept constant and the director remains normal to the layer. According to [31] this deformation imposes the following limitation to the director field:

$$\text{curl } \mathbf{L} = 0 \quad (2.26)$$

and, consequently, twist and bend elastic moduli diverge in the vicinity of the phase transition nematic-smectic A. Equation (2.24) is not valid for smectic C (and ferroelectric smectic C*) liquid crystals, where we also deal with three volume elastic constants. These points are discussed in more detail in the forthcoming chapters of the book.

Methods of the anchoring energy evaluations and the corresponding experimental data are given in Chapter 3. We should note, however, that the value of the effective anchoring energy, defined from (4.26), (4.27), depends on the form of the potential barrier $F_0^s(\theta)$ [28], (4.7). For sufficiently small values of anchoring energy the electrooptical response of the nematic cell becomes infinitely steep, so that for a certain critical value of W a hysteresis and first-order Frederiks transition are possible [27–31].

In the case of finite anchoring there also exists a saturation voltage for the total director reorientation, parallel (Fig. 4.1(a)) or perpendicular (Fig. 4.1(b)) to the field when the boundary regions disappear [27–31]. Development of the nematic cells with a good and reliable control of anchoring energy is of great importance for applications, as very steep transmission-voltage curves [27–31], memory states [30], and improved response times [27, 32] could be realized. In this section, we do not consider flexoelectric and surface polarization effects which will be discussed below.

4.1.6 Dynamics of the Frederiks Transition

It is easiest to examine the kinetics of the Frederiks effect for the experimental geometry shown in Fig. 4.4(c), since a pure twist or T deformation is not accompanied by a change in position of the centers of gravity of the molecules. In contrast, for S- and B-effects the rotation of the director is accompanied by such a change in position, i.e., by a movement of the liquid (back-flow). In order to allow for this back-flow the equation of motion of the director is coupled with that of the fluid.

For a pure T deformation the equation of motion of the director expresses the balance between the torques due to the elastic and viscous forces and the external field (and does not contain the fluid velocity) [33]

$$K_{22} \partial^2 \varphi / \partial x^2 + \Delta \chi H^2 \sin \varphi \cos \varphi = \eta \partial \varphi / \partial t, \quad (4.28)$$

This equation describes the director rotation in a magnetic field H with the inertia term $I \partial^2 \varphi / \partial t^2$ being disregarded, $\eta_1 = \alpha_3 - \alpha_2$ is rotational viscosity, and α_i are Leslie coefficients. Equation (4.28) in the limit of small φ angles, $|\varphi| \ll 1$, transforms to

$$K_{22} \partial^2 \varphi / \partial x^2 + \Delta \chi H^2 \varphi = \eta \partial \varphi / \partial t \quad (4.29)$$

with the solution

$$\varphi = \varphi_m \exp(t/\tau_r) \sin(\pi z/d), \quad (4.30)$$

where $\tau_r = \eta / (\Delta \chi H^2 - K_{22} \pi^2/d^2)$ is the relaxation or switching on time.

The solution (4.30) satisfies the strong anchoring boundary conditions

$$\varphi|_{z=0} = \varphi|_{z=d} = 0$$

and assumes a maximum φ value at the center of the layer $\varphi(z=d/2) = \varphi_m$.

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The corresponding relaxation or decay times are found from (4.29) for $H = 0$ in a similar way

$$\tau_d = \eta d^2 / K_{22} \pi^2, \quad (4.31)$$

The characteristic times remain the same when describing the dynamics of small T deformations in an electric field if the following substitution is made [34]:

$$\Delta \chi H^2 \rightarrow \Delta \varepsilon E^2 / 4\pi. \quad (4.32)$$

Taking into account the terms $\sim \varphi^3$ in (4.29) [35, 36] results in a more complicated expression for the director amplitude

$$\varphi_m^2(t) = \frac{\varphi_m^2(t \rightarrow \infty)}{1 + [\varphi_m^2(t \rightarrow \infty) / \varphi_0^2(t \rightarrow 0)] - 1} \exp(-t/\tau_1) \quad (4.33)$$

and does not change the characteristic times τ_1 , τ_d . In the general case, (4.28) can only be solved numerically.

Backflow

Unlike the T-deformation, the director reorientation in S- and B-effects is always accompanied by the macroscopic flow of a nematic liquid crystal (backflow) with the velocity $\mathbf{V} = (V(z), 0, 0)$, where the z -axis goes perpendicular to the substrates and SB-deformations take place in the x -plane. The velocity \mathbf{V} includes only the x -component, because the y -component is zero according to the continuity equation ($\text{div } \mathbf{V} = 0$), and the total system vanishes due to the symmetry of the problem (Fig. 4.6). The total system of dynamic equations for $V(z)$ and the director rotation angle $\theta(z)$ gives [37–39]

$$\rho \partial V / \partial t = \delta / \partial x (A \partial \theta / \partial x + B \partial V / \partial x), \quad (4.34)$$

$$\tilde{K} \partial^2 \theta / \partial x^2 + \Delta \varepsilon E^2 / 4\pi \sin \theta \cos \theta = \eta_1 \partial \theta / \partial t + A \partial V / \partial x,$$

where, for simplicity,

$$K_{11} = K_{33} = \tilde{K}, \quad |\Delta \varepsilon| \sin^2 \theta \ll \varepsilon_1, \quad (4.35)$$

i.e., the field E does not depend on the director angle θ (4.12), and

$$A = \alpha_3 \cos^2 \theta - \alpha_2 \sin^2 \theta, \\ B = \frac{1}{2} [2\alpha_1 \sin^2 \theta \cos^2 \theta + (\alpha_3 - \alpha_2) \sin^2 \theta + (\alpha_3 + \alpha_2) \cos^2 \theta + \alpha_4].$$

The boundary conditions for the director (4.16) and for the velocity

$$V|_{z=0} = V|_{z=d} = 0 \quad (4.36)$$

are also needed.

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The Physics of Liquid Crystals

SECOND EDITION

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Exhibit 4

10 LIQUID CRYSTALS: MAIN TYPES AND PROPERTIES

give smectics (and nematics) on one hand, columnar phases (and nematics) on the other, but not both with the exception of thermotropic soaps [13].

1.2.6 Summary

To summarize—we have found four types of building blocks:

- (1) small organic molecules, either rod-like or disk-like, for which an amphiphilic character may or may not be crucial (at least for getting the nematic phase). They are commonly designated as thermotropic;
- (2) rods in a liquid substrate. Here the temperature (T) effects are difficult to control (very often an increase in T will rapidly destroy the individual rods), and the natural parameter which we can adjust to induce phase transitions is the *concentration* of the rods. Such systems are called *lyotropic*;
- (3) main-chain or side-chain polymers that are thermotropic mesogens. Aside from temperature the molecular weight may also be considered as a variable;
- (4) amphiphilic compounds. These may give rise to associations and to mesomorphic behaviour, either in the presence of a selective solvent (e.g. water in soaps) or as a pure phase (for certain block copolymers and thermotropic soaps). Thus, depending upon which of the above conditions holds, amphiphilic compounds may be lyotropic or thermotropic.

In the present book, we shall be concerned only with thermotropic materials (except for a short discussion on biaxial nematics). Having in mind the various chemical species, we can now start to describe the unusual thermodynamic phases to which they give rise. The classification of mesophases (first clearly set out by G. Friedel in 1922 [14]) is essentially based on their symmetry. As we have seen there are three major classes: nematics; smectics; and columnar phases.

1.3 NEMATICS AND CHOLESTERICS

1.3.1 Uniaxial nematics

A schematic representation of the order of a 'nematic'† phase is shown in Fig. 1.4(a), (b). The main features are as follows.

† The word 'nematic' was invented by G. Friedel. It comes from the Greek *nema* = thread, and refers to certain thread-like defects that are commonly observed in these materials. The nematic

NEMATICS AND CHOLESTERICS

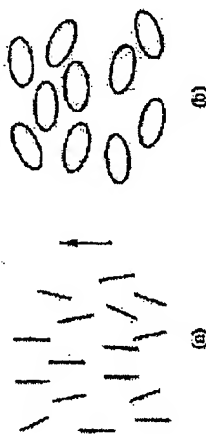


Fig. 1.4. The arrangement of molecules in the nematic mesophase: (a) made up of rod-like molecules; (b) made up of disk-like molecules.

1. The centres of gravity of the molecules have *no long-range order* and, consequently, as already stated, there is only diffuse scattering in the X-ray diffraction pattern. The correlations in position between the centres of gravity of neighbouring molecules are similar to those existing in a conventional liquid, aside from the anisotropy $\bar{\epsilon}_1 \neq \bar{\epsilon}_\perp$ in the length scale. In fact, nematics do flow like liquids. For a typical nematic such as PAA the viscosities are of order 0.1 poise.†
2. There is some order, however, in the *direction* of the molecules; they tend to be parallel to some common axis, labelled by a unit vector (or 'director') n . This is reflected in all macroscopic tensor properties for instance, optically, a nematic is a uniaxial medium with the optical axis along n . (The difference between refractive indices measured with polarization parallel or normal to n is quite large: typically 0.2 for PAA.) In all known cases, there appears to be complete rotational symmetry around the axis n .
3. The direction of n is arbitrary in space; in practice it is imposed by minor forces (such as the guiding effect of the walls of the container). This is a situation of broken rotational symmetry, reminiscent of a Heisenberg ferromagnet, where all spins tend to be parallel but where the energy is independent of the direction of the total moment M .

4. The states of director n and $-n$ are indistinguishable. For instance, if the individual molecules carry a permanent electric dipole, as in Fig. 1.5(a), there are just as many dipoles 'up' as there are dipoles 'down' and the system is not ferroelectric.

5. Nematic phases occur only with materials that do not distinguish between right and left; either each constituent molecule must be identical to its mirror image (achiral) or, if it is not, the system must be a 'racemic' (1:1) mixture of the right- or left-handed species (we shall come back to this point in Section 1.3.3). From a crystallographic point of view, properties 2, 4, and 5